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NEW CONCEPTS IN LIGHTWEIGHT ARMS

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The conflict in designing a robot which is fast for large motions and small motions as well as accurate can be alleviated by strategies of operation such as the one described in this paper, called the bracing strategy. Large motions are assigned to joints which move the major links. When these motions are completed the arm is "braced" against the workpiece or a passive workbench. The small motions are assigned to other degrees of freedom which are referenced to the workpiece rather than the base of the robot. In this way lighter arms are possible without their disadvantages for fast, accurate small motions. The concept and issues of its implementation are discussed.

1 Introduction

A robot requires an effective and efficient combination of intelligence at various levels and a mechanical manipulator. Technology for implementing the intelligence, including the lower level servo controls, is rapidly developing while the purely mechanical aspects are only slowly evolving. Various strategies must be employed to use intelligence in the form of controls and execution strategies to enhance the mechanical technologies and in improving the efficiency of an arm in manipulating a given payload weight. It is true in improving arm accuracy and dexterity as well. This paper discusses some ways of improving the ratio of payload weight to arm weight.

The rated payload of commercial robots today is 3% to 5% of the total arm weight. Current programs for heavily loaded arms allow about a second of settling time for arm oscillations to die out. These are facts indicative of a need to model and deal with arms as having compliant members both to deal with existing dynamics and to design more capable arms.

2 Lightweight Arms: Pros and Cons

Ultimately, one must have fast motion to have the highest performance for a robot arm. Most robot tasks consist of gross motion and fine motion phases. Gross motion involves large movements with a relatively predictable destination enabling trajectory planning. These motions require a high force to inertia ratio for rapid completion. Fine motion involves smaller, more precise movements which are less predictable. They are required after imprecise gross motions or could arise in response to disturbances, statistical variation in dimensions, or changes in the environment. To accomplish these motions quickly a high bandwidth servo system is required. Such bandwidth typically requires rigidity in the actuated structure, hence additional structural mass. The traditional approach accomplishes both gross and fine motions with the same actuators and linkage. Thus the structural mass required for the fine motion speed detracts from the gross motion speed. Correspondingly, a light and hence flexible arm will have low bandwidth when controlled by conventional means.

In addition to higher gross motion speed, other advantages exist. The advantages of lighter arms are summarized as follows:

1. Higher gross motion speeds can be obtained.

2. Cost of the mechanical subsystem can be reduced.

3. Energy efficiency is improved due to smaller actuators for the same cycle times.

4. Portability and mobility of arms is improved.

5. Safety is improved due to reduced moving mass.

6. Mounting requirements are reduced.

On the other hand problems arise due primarily to the greater flexibility of the arm. Strength of an arm is typically not the limiting constraint. Problems due to a lightweight arm include the following:

1. Bandwidth and hence fine motion speed are reduced, at least with conventional control schemes.

2. Vibrations (dynamic inaccuracies) may be excited by motions or external disturbances.

3. Static inaccuracies (droop) will occur in a gravitational force field.

4. Attempts to overcome the above disadvantages with improved controls will result in a more complicated control system.

5. The design and analysis of a flexible arm is much more complicated than for a rigid arm.

3 Limitations on the Control of Flexible Arms

The improved control of flexible, that is compliant, arms has been a research topic for a number of years. [Book, 1974] Recent studies show that the response of such an arm can be improved over conventional control algorithms intended for rigid arms. [Fukuda, 1984] [Truckenbrodt, 1981] These algorithms are limited with respect to their ability to respond to a disturbance on the arm. Their accuracy is inherently limited by the ability to detect the arm's deflection, as well as by joint sensors and their ability to totally eliminate vibrations. If one attempts to improve the speed of response of these algorithms without limit the robustness of the system may be compromised.

4 The Bracing Concept

The research underway seeks to eliminate the conflict between gross and fine motion speed. The configurations studied effectively reduce the distance from the end point to a "fixed" base during the fine motion phase by "**bracing**" it against a static structure or the work piece itself. This approach is especially relevant to long arms with light payloads. [Book, 1983] A wide range of tasks fall into this category including ultrasonic, visual, or other inspection of large objects, cleaning windows on multistory buildings, repairing transformers and insulators on utility poles, and assembly of space or underwater structures. A similar concept for teleoperator is being explored by the Canadian Electrical Association, and Robotic Systems International Ltd. and by Southwest Research Institute and EPRI for servicing power lines.

Bracing is analogous to the strategy of human workers who steady their hand for precise work by bracing their arm against a work bench as shown in Fig.1. It is also a variation of the strategy of extending the range of an arm by providing it with mobility. For mobile robots the strategy is typically to transport the arm to the vicinity of the work piece, deactivate the mobility subsystem, and activate the arm. Both cases are examples of allocation of the motion responsibilities to the most appropriate degrees of freedom. Similar approaches have been proposed by Moore and Hogan [Moore, 1983] and applied specifically to drilling.

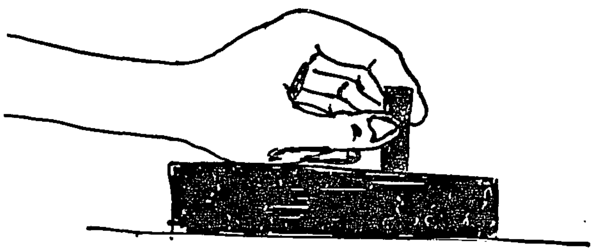

Fig. 1 Human employing bracing strategy.

Other examples of allocation of degrees of freedom to independent motions include:

- Conveyor belts and arms
- Arms and positioning tables
- Rockets, Lunar Landers, and Lunar Rovers
- Robot arms and positioning tables.

In these examples various means of effectively bracing one set of degrees of freedom from the remaining degrees of freedom are used. The means of bracing may inherently provide greater positioning accuracy relative to the workpiece than was previously available. Hence the Lunar Lander sitting on the surface of the Moon has a well defined height above the surface of the Moon. On the other hand, a positioning table which comes to rest has an accuracy only known as well as the sensors used in positioning it. Locating holes can be used in bracing an arm which accurately position an arm in several degrees of freedom relative to the workpiece. More versatile operation is possible if the accuracy of the position after bracing is obtained through end point sensing relative to the base, or better, relative to the workpiece.

Bracing requires supporting forces of the arm be developed in some manner. Consideration of several means of creating these forces have been considered. [Book, Le, Sangveraphunsiri, 1984] They include (1) a simple pressure contact, (2) mechanical clamping, (3) vacuum attachment, and (4) magnetic attachment. Multiple means may be appropriate in many cases.

The issues in controlling an arm to be braced are somewhat different than in controlling conventional robots. They can be broken down into issues of:

- Gross Motion
    1. Choosing a fast trajectory which does not unnecessarily excite vibrations
    2. Following the trajectory chosen with a controller that is accurate and stable over large changes in parameters
    3. Selecting a destination to allow best use of other degrees of freedom.
- Rendezvous and Inactive phases
    1. An accurate, gentle collision with bracing structure
    2. Passive damping of the high frequency dynamics
    3. Appropriate control of the statically indeterminate braced structure
- Fine Motion
    1. Sensing of position relative to target
    2. Fast, probably conventional control of fine motion degrees of freedom.

5 Conclusions

The bracing strategy holds promise for resolving design conflicts in achieving superior performance for certain types of applications. Economic questions of the value of the added complexity (increased number of degrees of freedom, more complex sensors and controls) can only be answered when research has made clearer what the payoff for this complexity will be in terms of performance.

Initial research in arm modeling, trajectory optimization, trajectory following, and terminal control is underway. [Book, 1984], [Sangveraphunsiri, 1984] This is now being tested on a single link arm experimentally. A two link large scale arm is planned for the near future.

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